Proposal IFPU

Early Universe and the Epoch of Reionization

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Abstract

The first billion years of the Universe define the current frontier of modern cosmology, both observationally and theoretically. During this time, the first stars and galaxies assembled from the primordial gas, and the atomic hydrogen permeating the early Universe became ionised. The epoch of reionisation (EoR) represents a major phase transition in cosmic history, which impacted almost every baryon in the Universe.

Recent results from independent, state-of-the-art probes of the reionization process (Planck collaboration 2018, arXiv:1807.06209; Kulkarni et al. 2019; Konno et al. 2018; Pentericci et al. 2018) suggest that the EoR was underway at z~9 and lasted below z~6.

Thanks to the increasing number of bright quasars detected at z ≥ 6 (e.g. Bañados et al. 2016; Wang et al. 2018 arXiv:1810.11926) it is now possible to pierce into the EoR. High-z bright quasars can be used both as signposts of big massive galaxies, whose properties can be studied in emissions and as background sources to study the intervening medium in absorption along the line of sight.

The nature of the first stars (so called PopIII stars), responsible for the reionization process, can be studied both locally, looking for the oldest and most metal-poor stars in our galaxy and in its close companions, and at the highest redshifts, determining the chemical abundances of the absorption systems in quasar spectra.

We propose a line of research to investigate these topics using state-of-the-art, multiband observations of high-z quasars and predictions from hydro-dynamical and semi-analytical models.

Project

The proposed line of research will develop into three interlaced topics:

1. First quasars and galaxies
2. First stars
3. The Cosmic UV Background

1. First quasars and galaxies

The mere presence of luminous quasars, powered by fast accretion ($>10\ M_\odot\ yr^{-1}$) onto massive ($>10^8\ M_\odot$) black holes (BHs) less than 1 Gyr after the Big Bang represents a challenge for models of massive BH formation and early galaxy growth.

Different models yield distinctive predictions on the time scales of the BH mass growth, on the typical Eddington rate, on the BH to host galaxy mass ratio, on the metallicity of the BH close environment, and on the galactic environment of the first quasars.

The first quasars are also benchmarks for investigating the first massive galaxies, that assembled together with the first SMBHs, and primeval galaxy overdensities which may eventually form the first proto-clusters. The QSO host galaxies are primarily studied through their cold gas and dust emission at (sub)mm wavelengths with ALMA and other radio facilities, which allow to resolve the kinematics and morphology of the gas and dust.
We will investigate these topics by:

A. Testing the models of massive BH formation by accurate BH mass and accretion rate measurements achieved via sensitive NIR spectroscopy of the Mg II emission line. To this aim we are collecting a sample of intermediate resolution, and signal-to-noise ratio spectra of more than 30 QSOs at $z>5.8$. Then, the inferred BH masses and Eddington rates can be compared with the host galaxy mass, star formation rate, and dust content (that is highly sensitive to metallicity) as revealed by mm wavelengths observations (e.g. Feruglio C., et al. 2018), providing direct insight on the competing build-up of BHs and stars in the first massive galaxies emerging from the dark ages. To carry out those measurements we are proposing to observe with ALMA all the objects in our optical/NIR sample.
B. Studying the properties of “normal” galaxies at the EoR by combining the information in absorption and in emission. The candidate galaxies can be selected in absorption as low ionization systems in the spectra of very high redshift QSOs, and then their properties can be derived from the observations in emission at (sub)mm wavelengths. We successfully applied this method to study a galaxy at $z\sim5.9$ (D’Odorico V, Feruglio C., et al. 2018) and we will enlarge the sample with new ALMA observations.
C. Using the properties of the observed primordial galaxies in terms of molecular and stellar masses to constrain the predictions of cosmological hydro-dynamical simulations modelling the formation of these galaxies together with their molecular and metal content (e.g. Vallini L. et al. 2018).

2. First stars

Understanding the nature and the evolution history of the first stars is fundamental both to clarify their role in the reionization process and to shed light on the physical mechanisms that drove their formation. Indeed, the First Stars are among the main science cases of new facilities such as the European Extremely Large Telescope (ELT), the Thirty Meter Telescope (TMT), and the James Webb Space Telescope (JWST). These new amazing telescopes aim at observing them directly, but none of these facilities will be operational before 2020.
Meanwhile, we can adopt other approaches. The First Stars were present also in our Galaxy and when they exploded, they left specific chemical patterns that we can observe in the oldest stars still floating in our halo and possibly in the oldest stars of the bulge.
A few rare very metal-poor stars (presumably very old) have been already observed and we expect to find many more in the next future, thanks to several ongoing and planned large-scale surveys in the galactic halo and bulge (e.g. APOGEE, LAMOST, Skymapper, and in the future 4MOST and WEAVE). These observational results show that stars with sub-solar masses and not only very massive stars formed out of almost primordial gas. However, the cooling and the physical processes are still to be understood.

Moreover, there have been important developments in stellar model calculations by different groups, with the inclusion of complex processes such as compact binary mergers, magnetic fields, neutrino winds, rotation, among others - able to provide the first quantitative estimations of the chemical yields for a large number of chemical elements.

Moving to redshifts $z \geq 6$ probed by QSOs in our samples, we can use low-ionisation metal lines to trace the dense gas in and around galaxies, offering insights into their interstellar medium and its chemical enrichment, analogous to the ways in which damped Ly-α systems (DLAs, defined by $N_{HI} \geq 10^{20.3}$ cm^{-2}) trace the kinematics and composition of lower-redshift galaxies (e.g. Wolfe et al. 2005 ARA&A, 43, 861). Also this chemical enrichment pattern can be used to constrain in a similar way the nature of the First Stars.

At present, there is no clear evidence of unusual abundance patterns in the 10 known systems at z ~ 5-6 that would indicate enrichment from exotic sources such as Population III stars.

These problems will be studied by:

A. Constraining the nature of the first stars with semi-analytical models developed by us, predicting the evolution and the metal enrichment in the ancient Galaxy, whose results will be compared with observations of the most metal poor stars;
B. Investigating in more details the properties of the most metal poor stars in our Galaxy through very high-resolution spectroscopic observations, to verify in particular the binarity nature of the Carbon enhanced stars (e.g. Bonifacio et al. 2018);
C. Increasing the sample of z~6 damped Ly-α systems thanks to our ongoing spectroscopic survey of z~5.8-6.6 QSOs, to improve its statistical significance and keep looking for the chemical signatures of PopIII stars (e.g. Becker G. et al. 2012).

3. The Cosmic UV Background

It is remarkable that after almost forty years the issue of the sources providing the cosmic ultraviolet background (UVB) driving the ionization process does not appear to be settled.

It is commonplace that galaxies should be able to produce the bulk of the UV emissivity at high redshift but the AGN population is also proposed as a relevant or dominant contributor. A direct measurement of the 1-4 Ryd photons escaping the various types of sources is unpractical at z>4.5 due to the reduced mean free path of these photons in the intergalactic medium (IGM). At lower redshift direct observations of galaxies, after accounting for the statistical contamination of interlopers, have in general provided upper limits in the fraction of ionizing photons, produced by young stars, that are able to escape to the IGM. These limits tend to be significantly lower than the ~ 20% required to re-ionize the Universe with galaxies only, and an increasing escape fraction with decreasing luminosity (possibly with a steep faint-end of the LF) has been invoked to circumvent this shortcoming. The corresponding escape fraction for QSOs is typically assumed to be about 100% but their space density at high redshift, still poorly known in particular at faint luminosity, is in general considered too low to provide the photons needed. The situation is so ambiguous that even exotic possibilities such as decaying particles cannot be totally excluded.

To tackle this problem we plan to investigate:

A. the intensity, spectral shape and homogeneity of the UVB at various redshifts by obtaining state-of-the-art high-resolution, high-SNR spectra of quasars and comparing them with simulations (e.g. Boera E., et al. 2019);

B. the escape fraction of galaxies in a wide range of mass/luminosity at redshifts for which the IGM is not too opaque ($z<4.5$) with deep observations in particular of intrinsically-faint lensed objects (e.g. Vanzella E., Nonino M., Cupani G., et al. 2018).
C. the luminosity function of AGN at high redshift, with particular emphasis on the low-luminosity regime (e.g. Boutsia K., et al., 2018).